



Tonks, Amanda J. and Aplin, Paul and Beriro, Darren J. and Cooper, Hannah and Evers, Stephanie and Vane, Christopher H. and Sjögersten, Sofie (2017) Impacts of conversion of tropical peat swamp forest to oil palm plantation on peat organic chemistry, physical properties and carbon stocks. *Geoderma*, 289 . pp. 36-45. ISSN 1872-6259

Access from the University of Nottingham repository:

http://eprints.nottingham.ac.uk/43906/1/Tonks%20et%20al.%20for%20Geoderma_18%20Oct.pdf

Copyright and reuse:

The Nottingham ePrints service makes this work by researchers of the University of Nottingham available open access under the following conditions.

This article is made available under the Creative Commons Attribution Non-commercial No Derivatives licence and may be reused according to the conditions of the licence. For more details see: <http://creativecommons.org/licenses/by-nc-nd/2.5/>

A note on versions:

The version presented here may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the repository url above for details on accessing the published version and note that access may require a subscription.

For more information, please contact eprints@nottingham.ac.uk

1 **Impacts of conversion of tropical peat swamp forest to oil palm plantation on peat**
2 **organic chemistry, physical properties and C stocks**

3 Amanda J. Tonks^{1,3}, Paul Aplin², Darren J. Beriro⁴, Hannah Cooper^{1,3}, Stephanie Evers³,
4 Christopher H. Vane⁴ and Sofie Sjögersten^{1*}

5

6 ¹The University of Nottingham, School of Biosciences, Division of Agricultural and
7 Environmental Science, Sutton Bonington Campus, Loughborough, LE12 5RD, United
8 Kingdom

9

10 ²Edge Hill University, St Helens Road, Ormskirk, Lancashire, L39 4QP, United Kingdom

11

12 ³The University of Nottingham Malaysia Campus, School of Biosciences, Semenyih,
13 Selangor Darul Ehsan 43500, Malaysia

14

15 ⁴British Geological Survey, Environmental Science Centre, Keyworth, Nottingham, NG12
16 5GG, United Kingdom

17

18 *Corresponding author: S. Sjögersten

19 E-mail: Sofie.Sjogersten@nottingham.ac.uk

20 Phone: +44 (0)7772993691

21

Abstract

Ecosystem services provided by tropical peat swamp forests, such as C storage and water regulation, are under threat due to encroachment and replacement of these natural forests by drainage-based agriculture, commonly palm oil. This study aims to quantify how the chemical and physical properties of peat change during land conversion to oil palm. This will be addressed by comparing four separate stages of conversion; namely, secondary peat swamp forests, recently [deeply](#) drained [secondary](#) forests, cleared and ~~deforested areas (with recently planted new~~ oil palm ~~plantation~~), and mature oil palm plantation in the vicinity of North Selangor Peat Swamp Forest, Malaysia. Results indicate accelerated peat decomposition in surface peats of oil palm plantations due to the lowered water table [and altered litter inputs](#) associated with this land-use change. ~~This reduced s~~Surface organic matter content and peat C stocks ~~from 1000 Mg ha⁻¹ in intact at secondary~~ forest sites [than to 500 Mg ha⁻¹ at mature oil palm sites \(C stocks were 1000 and 500 Mg ha⁻¹ at secondary forest and mature oil palm sites, respectively\)](#). Land conversion altered peat physical properties such as shear strength, bulk density and porosity, with mirrored changes above and below the water table. Our findings suggest close links between the degree of decomposition and peat physical properties through the entire depth of the peat profile. We have demonstrated that conversion from secondary peat swamp forest to [mature](#) oil palm plantation may seriously compromise C storage and, through its impact on peat physical properties, the water holding capacity in these peatlands.

Keyword: land use change; carbon stocks; oil palm; organic chemistry; peat decomposition; soil physical properties; tropical peat swamp forest

1. Introduction

Ombrotrophic tropical peat swamp forests are unique ecosystems [covering 247 778 km² in SE Asia and 441 025 km² globally \(Page *et al.*, 2011\)](#). ~~covering an estimated 2 to 2.5 million~~ perched on rich deposits of preserved organic matter are made possible by substantial rainfall, coupled with suitable topography and geology, which results in waterlogging. The anoxic and acidic conditions retard microbial decay (Andriesse, 1988; Page *et al.*, 2006; Yule and Gomez, 2009) resulting in peat accumulation as inputs of litter from the vegetation are greater than decomposition rates (Jauhiainen *et al.*, 2008).

These unique systems are valuable resources, contributing a multitude of ecosystem services. Above ground, tropical rainforests maintain areas of high biodiversity by providing habitats for a variety of species, many of which are endemic (Posa *et al.* 2011; Keddy *et al.*, 2009). Below ground, the sequestration of atmospheric carbon is interwoven into the fabric of the ecosystem (Jauhiainen *et al.*, 2008). An estimated 42,000 megatons of ancient carbon is stored in 12% of the total land area of Southeast Asia alone, making this one of the largest stores of terrestrial carbon on Earth (Wetlands International, 2014). Peat soil structure is responsible for ecosystem processes by controlling hydrology, which regulates hydrological features within the catchment. For example, its high organic matter content and low bulk density allows peat to act as a water reservoir, mitigating extreme conditions such as floods and droughts (Huat *et al.*, 2011; Wösten *et al.*, 2008).

Land use change over the past century has been a key driver of peatland degradation, with conversion to agriculture and forestry, and peat extraction sites, leading to artificially lowered water tables (Haddaway *et al.*, 2014). Limitations in understanding how peatland systems function has led to land degradation, which, for example has caused uncontrollable burning of over a million hectares of Indonesian peat during 1996, resulting from excessive land use

71 change by the Mega Rice Project (Page *et al.*, 2002). Land conversion to agricultural oil palm
72 plantation represents one of the primary threats to Malaysia's peat swamp forests (Koh *et al.*
73 2011). However, knowledge of the impact of the different land conversion stages involved in
74 the establishment of oil palm plantations, in terms of decomposition, C stocks and peat
75 physical properties, is extremely limited as most previous work has focused on binary
76 comparison of intact forest and mature oil palm plantations.

77 Drainage of peat swamp forests to support oil palm production intensifies peat degradation as
78 the thickness of the oxygenated zone of decay (acrotelm) is increased. This enhances rapid
79 aerobic microbial decay compared to anaerobic decomposition which predominates within
80 the anoxic zone below the water table (Anshari *et al.*, 2010). In addition to lowered water
81 tables, deforestation removes complex vegetation structures and replaces them with a
82 monoculture of oil palm trees, which deposit far less biomass, limiting organic matter inputs
83 (Anshari *et al.*, 2010). The combination of decreased biomass input and reduced preservation
84 of deposited biomass has caused large-scale peat degradation resulting in high atmospheric
85 CO₂ emissions (Hooijer *et al.*, 2010; Couwenberg *et al.*, 2010).

86 A greater degree of peat decomposition results in loss of structure as fresh litter is first broken
87 down to fibrous hemic peat, and then, following sustained decomposition, to sapric peat
88 (Wüst *et al.*, 2003). The progressing decomposition process alters the organic components
89 and chemistry due to loss of carbon and conversion of readily decomposable materials, such
90 as polysaccharides, celluloses and hemicelluloses, with only more recalcitrant compounds
91 such as lignin and humic substances remaining (Andriesse, 1988; Broder *et al.*, 2012; Kuhry
92 and Vitt, 1996; Yonebayashi *et al.*, 1994). Degradation of physical properties occurs through
93 subsidence as the open pore structure created by the fibrous, woody material collapses due to
94 oxidation, shrinkage and compression, reducing total porosity and increasing bulk density as
95 more solid material is concentrated per unit volume (Wösten *et al.*, 1997; Quinton *et al.*,

2000). As a consequence of degradation, percolation of water down the peat profile slows, decreasing hydraulic conductivity (Firdaus *et al.*, 2010). Water storage characteristics are also altered by decomposition as the water holding capacity is lowered and water retention increases, with implications for both the water content and gas flux rates within the peatlands (Boelter, 1964).

Knowledge on peat chemical and physical properties, as affected by the stages of land conversion for oil palm cultivation, is necessary to develop effective peatland management, and in the instance of degraded peatlands, restoration plans (Jauhianen *et al.*, 2008; GEC, 2014), thus conserving valuable ecosystem services. Land-use change in tropical peatlands is commonly discussed from the perspective of carbon emissions, with a very limited literature associated with peatland properties, and even fewer studies associated with multiple stages of conversion. This study determines how peat chemical and physical properties are altered during land conversion to oil palm. To achieve this we tested the following hypothesis: Land-use change of secondary peat swamp forests by drainage, clearance of forest [and planting of oil palm](#), and [finally](#) establishment of mature oil palm plantations, which involve lowering of the water table and altered litter inputs, will accelerate peat decomposition and reduce C storage in tropical peatlands. As a consequence of land-use change to oil palm plantation, we predict greater peat humification and loss of carbohydrates and carboxyl compounds relative to recalcitrant aromatic structures reflecting enhanced microbial decomposition in drained surface peat layers. We expect this enhanced decomposition to result in (i) peat subsidence and lower C stocks in mature oil palm plantations compared to secondary forest sites and areas under the initial stages of conversion and (ii) highest shear strength and bulk densities, but the lowest porosity at oil palm sites.

119

2. Study sites

~~The study site of North Selangor Peat Swamp Forest (NSPSF) is situated on a flat coastal plain about 10 km inland on the west coast of Peninsular Malaysia (Figure 1), (Yule and Gomez, 2009). This tropical ombrotrophic peat swamp covers 73,592 ha and includes 50,106 ha of the Sungai Karang Forest Reserve to the north and 23,486 ha of the Raja Musa Forest Reserve to the south (Ahmed, 2014). The main tree species found in the areas are: *Macaranga pruinosa*, *Campnosperma coriaceum*, *Blumeodendron tolbrai*, *Shorea platycarpa*, *Parartocarpus venenosus*, *Ixora grandiflora*, *Pternandra galeata*, *Cryptostachys sp.*, and *Pandanus atrocarpus* (Yule and Gomez 2009). Four land conversion classes were selected, with five replicate sites for each, to represent the stages involved in the process of conversion (ranging from intact forest to mature oil palm):~~

During the early Holocene, the area was likely colonised by extensive mangrove systems, but these diminished after the last Holocene interglacial marine incursion when the fresh water peatland vegetation started to take hold, resulting in the deposition of acidic peat up to 5 m deep, overlaying grey marine clay (Yule and Gomez, 2009). The area receives an average rainfall of over 2000 mm per year, with the driest month in June measuring 76 to 191 mm and the wettest month in November measuring 185 to 414 mm (Sim and Balamurugam, 1990; Yusop, 2002). Average shaded air temperature recorded was 28.5 °C, with an average monthly relative humidity of 77.2% (Hahn-Schilling, 1994).

The study site of North Selangor Peat Swamp Forest (NSPSF) is situated on a flat coastal plain about 10 km inland on the west coast of Peninsular Malaysia (Figure 1), (Yule and

Gomez, 2009). This tropical ombrotrophic peat swamp covers 73,592 ha and includes 50,106 ha of the Sungai Karang Forest Reserve to the north and 23,486 ha of the Raja Musa Forest Reserve to the south (Ahmed, 2014). The main tree species found in the areas are: *Macaranga pruinosa*, *Campospermacoriaceum*, *Blumeodendron tokbrai*, *Shorea platycarpa*, *Parartocarpus venenosus*, *Ixora grandiflora*, *Pternandra galeata*, *Cryptostachys sp.*, and *Pandanus atrocarpus* (Yule and Gomez 2009). Four land conversion classes were selected, with five replicate sites for each, to represent the stages involved in the process of conversion (ranging from intact forest to mature oil palm):

Stage 1. Shallowly drained forest sites – prior to conversion, intact secondary peat swamp forests where water tables are close to or at the surface for a large part of the year. maximum water table draw down was ca. 0.5-0.6 m in areas away from drainage ditches (GEC 2014).

Stage 2. Recently deeply drained forest sites – extensive drainage of peat swamp forests where large drainage ditches (2-3 meters wide and ca. 2 m deep) have been dug every few hundred meters in order to lower the water table, but trees and dense understory vegetation shrubs are left relatively intact have not been removed. In this case ditches were constructed c. 6 months prior to fieldwork.

Stage 3. Cleared Recently planted young oil palm sites – areas in which both drainage and deforestation has occurred, which subsequently is planted with oil palm seedlings (also c. 6 months prior to sampling).

Stage 4. Mature oil palm sites – fully mature oil palm plantations, in which drainage, deforestation, and establishment of oil palm trees for 10-15 years has occurred (age range of the sampling sites was estimated based on height of the oil palms). All the oil palm sites are first generation of oil palm. Water table monitoring within the NSPSF indicate

[maximum water table draw down to ca. 1.5 m below the surface during periods of low rainfall with water tables generally being below 0.5 m below the surface \(GEC 2014\).](#)

3. Materials and Methods

3.1. Field sampling

Within each of the land conversion classes, five ~~census~~ plots with areas of 900 m² were marked out during November and December of 2014. [The broad site selection was based on areal images and maps \(GEC 2014\). Forest sites were selected to be spatially distributed over NSPSF taking accessibility into account. Recently deeply-drained forest and recently plant oil palm plantations site were constrained to two areas of subject to this land use. Within these areas plots were selected randomly \(see below\). Mature oil palm areas were chosen to be as spatially distributed as possible but also site access.](#) Random number tables were used to determine the direction and distance to the south west corner of the plot, ensuring random selection of the plot within the broader site. GPS coordinates were recorded for each corner; locations for each plot are in Supplementary information 1.

In each of the census plots, a 1 dm³ block of surface peat and an entire peat core from surface to underlying grey marine clay were collected. The 10x10x10 cm peat blocks were measured with a ruler and carefully cut and lifted from the peat using a household bread knife and trowel, before sealing in large zipper storage bags. Peat cores were extracted using a side-filling Russian Peat Corer (Van Walt, UK) with a 50 cm long sampling chamber, allowing for the recovery of deep, uncompressed peat cores. Peat depth was determined at every site, recording the distance from the peat surface to the underlying clay layer. Immediately following extraction, peat samples were divided into 10 cm segments in the field. Samples were bagged and sealed to avoid moisture loss.

191 Surface peat volumetric water content was quantified at nine random locations within each
192 plot using a ML2X ThetaProbe Soil Moisture Sensor with HH2 Moisture Meter Readout Unit
193 (Delta-T Devices Ltd). Peat surface shear strength was gauged at the same nine locations
194 using a 33 mm Shear Vane.

Commented [SS2]: Data was used as a covariate to the shear strength data

195 Water table height was measured with a measuring tape, either from the peat surface to the
196 water surface if positive, or from the surface down to the water table depth using the borehole
197 left by the Russian Peat Corer if negative.

198 3.2.Laboratory analysis

199 3.2.1. Methods to determine peat chemical properties

200 For total carbon (C) and nitrogen (N) determination, peat samples were first oven dried at 105
201 °C for 48 hours and then ball milled for homogenisation using a Planetary Ball Mill (Retsch-
202 PM400, Castleford, UK). Analysis of C and N concentrations in the peat samples was
203 performed using a total element analyzer (Thermo Flash EA 1112, CE Instruments, Wigan,
204 UK).

205 The degree of decomposition was quantified using ~~two methods. First, the 10-point scale of~~
206 ~~von Post (1922) was used to indicate peat structure by ranking the state of decay of organic~~
207 ~~matter from H₁, very fibrous with little humification, to H₁₀, very few fibres with a high~~
208 ~~humification degree. The higher the number in the von Post scale, the higher the degree of~~
209 ~~humification (Huat *et al.*, 2011; Verry *et al.*, 2011; von Post, 1922). This was determined by~~
210 ~~squeezing a small sample of field-wet peat and assessing the proportion of peat which~~
211 ~~extruded through the fingers, the proportion left in the hand, and the colour and turbidity of~~
212 ~~the free liquid (Verry *et al.*, 2011). The proportions of each fraction that determine the H~~
213 ~~value has been translated from von Post (1922) into English and can be found in Stanek and~~

~~Sile (1977). H values were assessed for the surface peat blocks and through the entire peat~~
spectroscopy was used to: (i) determine the organic composition of surface peat, and (ii)
assess if its organic chemistry was altered by land conversion by comparing the relative
abundance of carbohydrates and carboxyls compounds to the abundance of aromatics.
Specifically we calculated the 3340/1630 and 1710/1630 ratios, where the wavenumbers
correspond to carbohydrates (3340), carboxyls (1710) and aromatics (1630) (Cocozza *et al.*,
2003; Artz *et al.*, 2008).~~;- these are subsequently denoted carbohydrates/aromatic ratio and~~
~~carboxyl/aromatic ratio, respectively.~~ In this instance, the higher the ratio, the higher the
proportion of readily decomposable compounds to aromatics, and the lower the degree of
decomposition.

Spectra were obtained using a Bio-Rad FTX3000MX series FTIR (Digilab Div., Bio-Rad
Laboratories, Cambridge, MA) and a diffuse reflectance auto sampler attachment (Pike
Technologies Inc. Madison, WI), using a similar method to that described by Vane (2003).
Each acquisition measured wavenumbers 4000 to 400 cm⁻¹ with 4 cm⁻¹ spectral resolution
and 40 scans. Samples were rotated 90° before repeating the analysis, allowing elimination of
any variation due to an uneven surface. Sample spectra were referenced against a powdered
potassium bromide matrix at the same instrument settings to produce a background spectra;
which was used to eradicate the interference of carbon dioxide and water vapour in the air.
All spectra were baseline corrected and the peak heights specific to readily decomposable
organic compounds were divided by peak heights specific to recalcitrant aromatic compounds
to generate decomposition indexes.

Surface peat pH was determined by diluting 5 cm³ of field-wet peat in 12.5 cm³ of distilled
water in oakridge centrifuge tubes and leaving on a rotary shaker overnight, before measuring
with a pH 209 benchtop pH meter (Hanna Instruments Ltd.) and combination pH electrode.

238 3.2.2. *Methods to determine peat physical properties*

239 Peat water content, bulk density, total porosity, and organic matter content were determined
240 for all surface peat blocks and entire peat columns at 10 cm intervals. Gravimetric water
241 content was assessed by oven drying the peat at 105°C for 48 hours. The peat mass was
242 recorded before and after oven drying and applied to Equation (1). Bulk density was
243 determined using the oven dried mass and known volumes, as in Equation (2). Total porosity
244 was derived from bulk density using Equation (3) and an average particle density for peat of
245 1.4 g cm⁻³ (Rowell, 1994). Organic matter contents were quantified using the loss on ignition
246 method. 5 g of oven dried, ball milled peat were weighed into porcelain crucibles, before
247 placing in a Carbolite AAF muffle furnace (Carbolite Ltd.) at 550 °C for 4 hours. The weight
248 of ash left after ignition was recorded and Equation (4) was used to determine the percentages
249 of organic matter.

250

251
$$\Theta = \frac{M_w - M_d}{M_d} \times 100 \quad (1)$$

252 Where Θ is the gravimetric water content, dry weight basis (%); M_w is the mass of wet peat
253 (g); and M_d is the mass of oven dry peat (g).

254

255
$$\rho_{\text{bulk}} = \frac{M_d}{V} \quad (2)$$

256 Where ρ_{bulk} is the bulk density, dry weight basis (g cm⁻³); M_d is the mass of oven dry peat (g);
257 and V is the volume of the peat core (cm³).

258

259
$$\phi = 1 - \frac{\rho_{\text{bulk}}}{\rho_{\text{particle}}} \times 100 \quad (3)$$

260 Where ϕ is the total porosity (%); ρ_{bulk} is the bulk density, dry weight basis (g cm^{-3}); and
261 ρ_{particle} is the particle density (g cm^{-3}).
262
263

$$264 \quad \text{OM} = \frac{M_1 - M_2}{M_1} \times 100 \quad (4)$$

265 Where OM is the organic matter content (%); M_1 is the mass of oven-dry peat (g); and M_2 is
266 the mass of ash left after ignition (g).

267 *3.2.3 Estimating C stocks*

268 We calculated C stocks at each site by predicting C concentration throughout the entire peat
269 profile using a transfer function between C content (which was analysed for 168 selected peat
270 samples) and LOI which was analysed for each 10 cm peat section. The C density in each 10
271 cm sample was then calculated using bulk density and summed over the entire peat profiles to
272 generate C stocks. Comparisons among land conversion stages were done using the stock
273 difference method (Hergoualc'h and Verchot 2011).

274 *3.3. Statistical analysis*

275 GenStat 17th edition statistical analysis software was used to evaluate all data generated from
276 this project. Shear strengths were analysed using linear mixed models with restricted
277 maximum likelihood (REML) to compare between land conversion classes by allowing the
278 incorporation of both fixed and random effects into the model accounting for environmental
279 variation between sites. Volumetric water content was added as a covariate when analysing
280 for differences between land conversion classes for shear strength as this variable accounted
281 for a high proportion of between-site variation.

One-way analysis of variance (ANOVA) was used to determine significant differences in the $3340\text{carbohydrate}/4630\text{-aromatic}$ and $4710\text{carboxyl}/4630\text{-aromatic}$ ratios among land conversion class. Two way ANOVAs were used to analyse significant differences between land conversion class, depth, and their interaction, allowing the incorporation of more than one discrete variable into the model. Continuous profiles of data for ~~von Post H-values,~~ gravimetric water content, bulk density, porosity, ash and organic matter content with depth were categorised into three distinct groups in order to run the two way ANOVA: surface peat, peat just below the water table, and the deepest peat horizon within each core which was above the clay layer (subsequently denoted “deep peat”), for the ANOVA three sub samples from each layer from all cores were used.

4. Results

4.1. Peat chemical properties

Peat pH values increased with conversion ($F_{3,19}=4.37$, $P < 0.05$) specifically pH ranged from 3.4 ± 0.06 , 3.7 ± 0.06 , 3.7 ± 0.08 , to 3.97 ± 0.08 at forest sites, deeply drained sites, recently planted and mature oil palm sites, respectively rising to 3.7 to 4.1 at oil palm plantations.

The peat C content did not differ significantly with either depth or among the land conversion classes (Figure 2a) while the N content was highest in the surface peat and in the recently drained forest area (Figure 2b). Consequently the C/N ratios were considerably higher in the two deeper peat layers but did not differ overall among sites (Figure 2c). C, N and C/N ratios through the individual peat profiles are shown in Supplementary information 3.

~~Surface peats (0–30 cm depth) from the oil palm plantations were more humified, i.e. had~~
 3). Broad peaks were observed at approximately 3340 cm^{-1} which are associated with O–H stretching of hydrogen in bonded O–H groups, specific to cellulose and other polysaccharides (Vane, 2003). Two sharp peaks observed at 2920 and 2850 cm^{-1} were due to asymmetric and symmetric C–H stretching of $-\text{CH}_2-$ groups from aliphatic compounds such as fats, waxes, and lipids. Shoulders were observed at approximately 1710 cm^{-1} on the side of 1630 cm^{-1} peaks, associated with C=O stretching of $-\text{COOH}$ or $-\text{COOR}$ groups present in carboxyl compounds. Broader peaks at 1630 cm^{-1} were assigned to aromatic C=C stretching and asymmetric $-\text{COO}-$ stretching of lignin and other aromatics. The distinct peak at 1510 cm^{-1} were assigned to aromatic C=C stretching vibrations in lignins (Vane, 2003). Three peaks of similar height and width were observed at 1450 , 1420 , and 1370 cm^{-1} , indicating O–H and C–H deformations in aliphatic and phenolic structures (Artz *et al.*, 2008; Gandois *et al.*, 2013; Vane, 2003).

The decomposition indexes, i.e. the ~~$3340/1630$ (carbohydrate/aromatics)~~ and ~~$1710/1630$ (carboxyl/aromatics)~~ ratios, in the surface peat differed significantly between land conversion classes (Figures 4a and 4b). Specifically, the $3340/1630$ ratio were significantly higher in forest and cleared sites (12.3 ± 1.2 and 16.4 ± 3.2 respectively), relative to drained and oil palm sites (8.5 ± 0.5 and 8.5 ± 0.8), ($F_{(3,16)}=5.64$, $P=0.008$, $r^2=0.51$), indicating higher proportions of aromatic structures relative to carbohydrates in drained and oil palm acrotelms (Figure 4a). $1710/1630$ ratios were significantly higher in the surface peats of cleared sites (1.8 ± 0.2), relative to other sites with ratios between 1.0 and 1.1 ± 0.1 ($F_{(3,16)}=5.62$, $P=0.008$, $r^2=0.51$), which suggests higher proportions of carboxyl groups relative to aromatic compounds within acrotelms at cleared sites (Figure 4b).

4.2 Peat depth and C stocks

Peat depths ranged between 125 and 273 cm with the greatest accumulation of peat found at the recently drained forest sites and the shallowest at the oil palm plantations (near significant effect, Figure 5a). In contrast, C stocks were highest at the forest sites at $ea, 1000-975 \pm 151$ Mg ha⁻¹ and lowest at the oil palm sites at $ea, 500-497 \pm 157$ Mg ha⁻¹, which suggests oil yield half the C stocks of those found at the forest sites (Figure 5b). Peat depth was a reasonable predictor of C stocks ($R^2 = 0.55$) (Figure 5c), however, the discrepancy between peat depth and C stocks among the different land conversion classes shows that bulk density and C concentrations impact the C stocks.

4.3 Peat physical properties

The position of the water table at the time the peat cores were collected was 6.0 ± 22 , -14 ± 23 , -39 ± 15 , and -21 ± 18 cm at the forest, drained, cleared, and oil palm sites, respectively, with positive values indicating the water surface being above the peat ($F_{(3,44)}=5.45$, $P<0.05$). The position of the water table was reflected in the volumetric surface moisture content which was 82.3 ± 28 , 46.3 ± 22 , 33.3 ± 9 , and 56.56 ± 21 % at the forest, drained, cleared, and oil palm sites, respectively. Shear strength was significantly different among land conversion classes ($F_{(3,20)}=3.49$, $P=0.035$, $SED=0.959$ using volumetric water content as a covariate), with higher values found at the oil palm plantations (9.7 ± 0.6 kPa) than the other land conversion classes (8.4 ± 0.6 , 6.8 ± 0.9 , and 7.8 ± 0.6 kPa for forest, drained and recently cleared sites, respectively).

Surface organic matter content was highest at forest sites ($94.1 \pm 1.5\%$) and lowest in oil palm plantations ($77.3 \pm 5.9\%$) (Figure 6a). In line with the field measurements of volumetric soil moisture content, forest sites had significantly higher water content ($627 \pm 90\%$) in the surface layer than oil palm sites ($440 \pm 42\%$) (Figure 6b; Supplementary information 54). Peat at drained and cleared sites had higher moisture content below the water table, than at the

mature oil palm plantations. Bulk density was displayed the opposite trend with lowest at the a bulk density of 0.07 g cm^{-3} , while surface and the other land conversion classes having were slightly higher at between $0.10\text{-}0.12 \text{ g cm}^{-3}$ for the other land conversion classes (Figure oil palm plantations both at the surface and at the two deeper layers.

Surface porosity was high for all land-use classes with the highest porosity observed at drained sites ($95.2\pm0.4\%$) (Figure 6e6d). Porosity then dropped as land conversion progressed to cleared and mature oil palm plantations across the peat profile. Bulk density displayed the opposite trend with lowest surface bulk density of 0.07 g cm^{-3} at drained sites, while surface bulk densities were slightly higher at $0.10\text{-}0.12 \text{ g cm}^{-3}$ for the other land conversion classes (Figure 6d). The peat then became denser at cleared and mature oil palm plantations both at the surface and at the two deeper layers.

5. Discussion

5.1. Changes in peat organic chemistry, humification, and C stocks following land use change

The higher carbohydrate/aromatic ratio~~3340/1630 ratio~~ (Figure 4a) found in forest and cleared surface layers suggests greater abundance of fresh litter inputs as a high ratio indicates a relatively high proportion of cellulose to aromatic compounds, which is typical of poorly decomposed peat (Cocozza *et al.*, 2003). Although continual, natural levels of litter inputs occurred both in forest and drained sites, only forest sites were observed to have the high water tables capable of preserving the cellulose-rich organic matter. The lower carbohydrate/aromatic ~~3340/1630~~ ratio at oil palm sites therefore indicates enhanced peat decomposition at this site. The fact that the carbohydrate/aromatic~~3340/1630~~ ratio was highest at the cleared site was unexpected. We speculate this is due to incorporation of carbohydrate rich woody debris (observed during sampling), from the recent deforestation into the top peat horizon during soil preparation (Andriesse, 1988). Indeed, the high proportion of carboxyl structures relative to aromatics, indicated by the ~~1710/1630~~carboxyl/aromatic ratios in surface peat at cleared sites (Figure 4b), indicate productions of carboxyls from the decomposition of recently deposited plant tissues in the surface peat (Cocozza *et al.*, 2003).

The ~~higher degrees of humification (higher H values on the von Post scale, Figure 2d) and~~ lower organic matter contents (Figure 6a) in the drained surface layer at the drained, cleared and oil palm sites provides further evidence that the conversion process stimulated decomposition. However, the enhanced decomposition following drainage was only evident when comparing forest to mature oil palm plantation, which suggests that C loss from oxidative decay is controlled in part by exposure time to air, as well as being influenced by fertiliser inputs, which also enhance decomposition (Wösten *et al.*, 1997; Anshari *et al.*,

2010; Corley *et al.*, 2003). ~~The greater degree of humification in surface peats relative to the deeper peat layers of drained and cleared forest, and oil palm indicates loss of structure and enhanced decomposition rates in surface peats (Figure 2d). This contrasts to the forested sites with water tables close to or at the peat surface, where the greatest decomposition degree was found in the deepest layers of peat (Kuhry and Vitt, 1996).~~

~~Although the H values were highest at the surface of the oil palm sites, the high degree of decomposition (H values ranging from about 7 to 10) found throughout the entire forest peat profiles (Appendix: Figure 1a) are intriguing as they contrast to studies of temperate and boreal peatlands where surface peat tends to have much lower H values (Kuhry and Vitt, 1996; Frohking *et al.*, 2001).~~ The DRIFT spectra presented in Figure 3 display the majority of peaks corresponding to temperate peatlands (Artz *et al.*, 2008; Coccozza *et al.*, 2003).

However, the latter usually show an additional broad peak between 1080 and 1030 cm⁻¹ which is not prominent here. This peak is assigned to C–O stretching and O–H deformation within polysaccharides (Artz *et al.*, 2008) and its low intensity in all surface peats, including forest sites, suggests rapid decomposition of polysaccharides ~~in line with the high H values.~~

This could be due to impacts of historical logging activities prior to the 1980s or to vegetation structure and litter inputs. Furthermore, peat swamp forests have both increased aeration associated with large tree roots (Hoyos-Santillan *et al.*, 2016), and an open pore structure provided by the fibrous wood input (in contrast to the shallow rooted, less fibrous sphagnum moss that dominates northern peatlands (Wüst *et al.*, 2003)), which together may contribute to aerobic microbial decay throughout the rhizosphere. The early decay of polysaccharides observed here as compared to temperate peatlands may also be enhanced by the higher ambient air temperatures in Malaysia. For example, fungal decay studies have shown that aerobic oxidative degradation of polysaccharides by white and soft rot fungi (the most vigorous of all wood-decay microbes) is optimal at temperatures between 20 to 40°C (Vane,

2003; Vane *et al.*, 2001). Similarly, a study of carbon cycling in tropical mangroves showed that arboreal termites cause extensive polysaccharide decay in leaf and wood litter due to symbiotic bacteria; this suggests that in tropical environments, litter may undergo extensive multi-phase (insectivorous and microbial) alteration prior to burial (Vane *et al.*, 2011).

~~The forest C stocks were within the lower range of those reported from peat swamp forests in~~
~~The large reductions in peat depth, of up to 2 m after 25 years of oil palm cultivation on~~
~~drained peatland, demonstrated by Hooijer *et al.* (2012) further support the notion of dramatic~~
~~C losses due to peat oxidation following drainage. Although the original peat depths at the oil~~
~~palm sites are not known, peat depths in adjacent peatland areas (ca. 1–2 km away from the~~
~~oil palm sites) are ca. 4 m (unpublished data not included in this study, Sofie Sjogersten)~~
~~indicating that rapid peat subsidence and C losses have occurred during the establishment of~~
~~mature oil palm plantations. Importantly, C loss rates measured in our study were higher than~~
~~those reported for Central Kalimantan, Indonesia of $10.8 \pm 3.5 \text{ Mg C ha}^{-1} \text{ year}^{-1}$~~
~~(Hergoualc'h and Verhot 2011) and the loss rates of $1400 \text{ Mg C ha}^{-1}$ over 100 years~~
~~predicted by modelling studies by Kurianto *et al.* (2015) indicating that substantial C loss~~
~~can occur quickly following conversion of peat swamp forests to oil palm plantations. Our~~
~~findings contrasts starkly to the minor changes in C stocks in mineral soil following~~
~~conversion of forest to oil palm plantation in Indonesia (53.63 ± 5.98 and $51.85 \pm 18.95 \text{ Mg}$~~
 ~~C ha^{-1} in forest and oil palm plantations, respectively; Khasanah *et al.*, 2015). Indeed, our~~
~~peatland study strongly refutes the concept of C neutral oil palm plantations, as suggested for~~
~~mineral soil systems by Khasanah *et al.* (2015). The large C losses from the peat shown in~~
~~our study, together with losses of the large tree biomass held in intact peat swamp forests~~
~~(ranging between 125 to 160 Mg C ha^{-1} assuming a 50% C content in the vegetation;~~
~~Kauffman *et al.*, 2011; Kornseder *et al.*, 2012; Toriyama *et al.*, 2014; Schlund *et al.*, 2015), is~~
~~nowhere near replaced by oil palm vegetation, which has an estimated life span above ground~~

Formatted: Font color: Accent 1

~~biomass of $30 \pm 10 \text{ Mg C ha}^{-1}$ (Germer and Sauerborn 2008). Indeed, this investigation points~~

The peat porosity and bulk density at forest sites were comparable to those found in tropical peatlands in Malaysia and elsewhere. For example, Firdaus *et al.* (2010) found porosities and bulk densities of $91.5 \pm 1.8\%$ and $0.112 \pm 0.004 \text{ g cm}^{-3}$, respectively, in forest surface peats. Other tropical peat studies have found bulk densities ranging from 0.02 to 0.21 g cm^{-3} , correlating with this study (Page *et al.*, 2004; Rieley and Page, 2008; Wösten *et al.*, 2008; Page *et al.*, 2011). Decomposition decreases the proportion of coarse, hollow fibres in peat as organic particle size and organic matter content (Figure 6a) is reduced with land conversion, and is expected to form a dense, closed soil structure (Huat *et al.*, 2011). In this study, enhanced decomposition, potentially in combination with compaction from machinery, following land conversion resulted in greater shear strength and lower soil moisture content in the surface peat layer at oil palm sites. The lack of a linear response of [bulk density and porosity](#) as land conversion progressed from intact peat swamp forest, through forest drainage and clearance, to mature oil palm (Figures 6c and 6d), may be linked to initial subsidence of the drained peat layers below the surface network of roots resulting in high porosity and low bulk density. We speculate that the subsequent decreased porosity and increased bulk density at the cleared and oil palm sites are due to the removal of lignified root biomass during the ground preparation, together with greater decomposition rates, resulting in denser peats over time (Huat *et al.*, 2011; Quinton *et al.*, 2000). It is also worth noting that the gradual reduction in peat gravimetric moisture content and porosity moving from drained to oil palm sites, is also evident below the water table, which may be linked to peat subsidence following drainage (Wösten *et al.*, 1997).

[5.3 Variation in peat depth and C stocks among land conversion classes](#)

The peat C stocks in the forest were within the lower range of those reported from peat
 swamp forests in SE Asia (Warren *et al.*, 2012; Comas *et al.*, 2015; Farmer *et al.*, 2014) and
 the pan-tropics (Kauffman *et al.*, 2011; Lhteenoja *et al.*, 2012; Draper *et al.*, 2014). The
 comparatively low C stocks are due to the relatively shallow peat depths at the forest sites
 around the edges of the peatlands (Figure 1). As peat depth in the central areas (not used in
 this study) of the NSPSF are >4 m (GEC 2014), C stocks are therefore likely to be
 substantially higher in the interior parts of the peatland than our estimates. We expected that
 enhanced decomposition rates following conversion to oil palm plantations, would result in
 peat subsidence and reduced C stocks compared to forest sites. This prediction was supported
 by the shallower peat depths and C stocks found in oil palm plantations (51% reduction in C
 stocks; Figure 5) compared to other land conversion classes. These findings suggests that
 increased decomposition rates following drainage and establishment of mature oil palm
 plantations have dramatically and rapidly reduced peat swamp forest C stocks. Large
 reductions in C stocks are in line with Farmer *et al.* (2014) who found a 30% decrease in C
 stock on oil palm as compared to intact peat swamp forest in Sumatra, Indonesia.

Commented [SS4]: Check reference

The large reductions in peat depth, of up to 2 m after 25 years of oil palm cultivation on
 drained peatland, demonstrated by Hooijer *et al.* (2012) further support the notion of dramatic
 C losses due to peat oxidation following drainage. Although the original peat depths at the oil
 palm sites are not known, peat depths in adjacent peatland areas (ca. 1-2 km away from the
 oil palm sites) are ca. 4 m (unpublished data not included in this study, Sofie Sjogersten)
 indicating that rapid peat subsidence and C losses have occurred during the establishment of
 mature oil palm plantations. Importantly, C loss rates measured in our study were higher than
 those reported for Central Kalimantan, Indonesia of $10.8 \pm 3.5 \text{ Mg C ha}^{-1} \text{ year}^{-1}$
 (Hergoualc'h and Verchot 2011) and the loss rates of $1400 \text{ Mg C ha}^{-1}$ over 100 years

488 predicted by modelling studies by Kurinanto *et al.* (2015) indicating that substantial C loss
489 can occur quickly following conversion of peat swamp forests to oil palm plantations. Our
490 findings contrasts starkly to the minor changes in C stocks in mineral soil following
491 conversion of forest to oil palm plantation in Indonesia (53.63 ± 5.98 and 51.85 ± 18.95 Mg
492 C ha⁻¹ in forest and oil palm plantations, respectively; Khasanah *et al.*, 2015). Indeed, our
493 peatland study strongly refutes the concept of C neutral oil palm plantations, as suggested for
494 mineral soil systems by Khasanah *et al.* (2015). The large C losses from the peat shown in
495 our study, together with losses of the large tree biomass held in intact peat swamp forests
496 (ranging between 125 to 160 Mg C ha⁻¹ assuming a 50% C content in the vegetation;
497 Kauffman *et al.*, 2011; Kornseder *et al.*, 2012; Toriyama *et al.*, 2014; Schlund *et al.*, 2015), is
498 nowhere near replaced by oil palm vegetation, which has an estimated life span above ground
499 biomass of 30 ± 10 Mg C ha⁻¹ (Germer and Sauerborn 2008). Indeed, this investigation points
500 towards a substantial C footprint of oil palm plantations on tropical peatlands.

501
502 These findings demonstrate that land conversion for oil palm plantations changed peat
503 physical properties over time through a combination of physical collapse of the peat structure
504 following drainage, and enhanced decomposition in the drained surface peats. It is likely that
505 such changes in peat physical properties are irreversible, particularly in the instance of
506 changes cause by enhanced decomposition. This has important implications for land
507 management policies, as some ecosystem services linked to the peat physical properties, e.g.
508 water holding capacity (Abdul Rahim & Yusop 1999), may be permanently, and negatively,
509 affected by land conversion for oil palm plantation. Indeed, peatland restoration, which is
510 currently implemented at degraded peatland sites across SE Asia (e.g. Jauhianen *et al.*, 2008)
511 and specifically within this study catchment (GEC 2014), may recover the biodiversity, fire
512 regulation and C sink capacity of peatlands, however, this may not be the case for the water

513 regulation services as these closely link to peat organic matter content, structure, density and
514 porosity (Firdaus *et al.*, 2010).

515

516 **Acknowledgements**

517 We thank the Royal Geographical Society (with IBG) for funding this project through the
518 Ralph Brown expedition award (to PA), with additional support from the University of
519 Nottingham. We are very grateful to the Selangor State Forestry Department for granting
520 forest reserve access and in providing field ranger support (including Mr Mohd Rosli B. Md
521 Kadim (Rosli), Mr Sabaruddin Mohd Shahid (Din) and the rest of the team at Raja Musa and
522 Sungai Karang Forestry Offices) as a follow-up to the 2013 Biodiversity Expedition
523 organised in association with Malaysia Nature Society; and also to staff at the Global
524 Environment Centre, Selangor, and especially Miss Hannah Cooper, for fieldwork assistance.
525 We also thank PKPS Agricultural Development Corporation for granting site access. We are
526 grateful to Mr James Verran, Mr Saul Vazquez Reina and Mr John Corrie for assistance in
527 the laboratory. CHV publishes with permission of the Executive Director, British Geological
528 Survey (NERC).

529

530 **References**

531 Abdul Rahim, N. & Yusop, Z., 1999. Hydrological impacts of forestry and land-use
532 activities: Malaysian and regional experience, 86-105. In: Water: forestry and land use
533 perspectives; Technical documents in hydrology; Vol.:70; 2004, Available at:
534 <http://unesdoc.unesco.org/images/0013/001379/137954e.pdf> [Accessed April 10, 2016]

535 Ahmad, N. (2014) *Guardians of the North Selangor Peat Swamp Forest* [online]. Peatlands
 536 International, Issue 2.2014. Available at:
 537 <https://peatlandsinternational.wordpress.com/2014/06/20/peatlands-international-2-2014/>>
 538 [accessed 17 April 2015].

539 Andriesse, J. (1988) *Nature and management of tropical peat soils* [online]. FAO Soils
 540 Bulletin 59. FAO - Food and Agriculture Organization of the United Nations, Rome.
 541 Available at: <<http://www.fao.org/docrep/x5872e/x5872e00.htm#Contents>> [Accessed 16
 542 October 2014].

543 Anshari, G., Afifudin, M., Nuriman, M., Gusmayanti, E., Arianie, L., Susana, R., Nusantara,
 544 R., Sugardjito, J., and Rafiastanto, A. (2010) Drainage and land use impacts on changes in
 545 selected peat properties and peat degradation in West Kalimantan Province, Indonesia.
 546 *Biogeosciences*. Vol. 7, no. 11, pp. 3403-3419.

547 Artz, R., Chapman, S., Robertson, A., Potts, J., Laggoun-Défarge, F., Gogo, S., Comont, L.,
 548 Disnar, J., and Francez, A. (2008) FTIR spectroscopy can be used as a screening tool for
 549 organic matter quality in regenerating cutover peatlands. *Soil Biology and Biochemistry*.
 550 Vol. 40, no. 2, pp. 515-527.

551 Boelter, D. (1964) Water storage characteristics of several peats in situ. *Soil Science Society*
 552 *of America Journal*. Vol. 28, no. 3, pp. 433-435.

553 Broder, T., Blodau, C., Biester, H., and Knorr, K. (2012) Peat decomposition records in three
 554 pristine ombrotrophic bogs in southern Patagonia. *Biogeosciences*. Vol. 9, no. 4, pp. 1479-
 555 1491.

556 Corley, R. Hereward V., and Tinker, P. (2003) *The Oil Palm*. 4th edition. Blackwell Science
 557 Ltd.

558 Coccozza, C., D'orazio, V., Miano, T., and Shotyk, W. (2003) Characterization of solid and
 559 aqueous phases of a peat bog profile using molecular fluorescence spectroscopy, ESR and
 560 FT-IR, and comparison with physical properties. *Organic Geochemistry*. Vol. 34, no. 1, pp.
 561 49-60.

562 Douglas, I. (1996) The impact of land-use changes, especially logging, shifting cultivation,
 563 mining and urbanization on sediment yields in humid tropical Southeast Asia: a review with
 564 special reference to Borneo. *IAHS Publications-Series of Proceedings and Reports-Intern*
 565 *Assoc Hydrological Sciences*. Vol. 236, pp. 463-472.

566 Firdaus, M., Gandaseca, S., Ahmed, O., and Majid, N. (2010) Effect of converting secondary
 567 tropical peat swamp forest into oil palm plantation on selected peat soil physical
 568 properties. *American Journal of Environmental Sciences*. Vol. 6, no. 4, pp. 402-405.

569 Frolking, S., Roulet, N., Moore, T., Richard, P., Lavoie, M., and Muller, S. (2001) Modeling
 570 northern peatland decomposition and peat accumulation. *Ecosystems*. Vol. 4, no. 5, pp. 479-
 571 498.

572 Gandois, L., Cobb, A., Hei, I., Lim, L., Salim, K., and Harvey, C. (2013) Impact of
 573 deforestation on solid and dissolved organic matter characteristics of tropical peat forests:
 574 implications for carbon release. *Biogeochemistry*. Vol. 114, no. 1-3, pp. 183-199.

575 GEC (Global Environment Centre), 2014. Integrated Management Plan for North Selangor
 576 Peat Swamp Forest 2014-2023 for Selangor State Forestry Department. , (June), p.183.

577 Haddaway, N., Burden, A., Evans, C., Healey, J., Jones, D., Dalrymple, S., and Pullin, A.
 578 (2014) Evaluating effects of land management on greenhouse gas fluxes and carbon balances
 579 in boreo-temperate lowland peatland systems. *Environmental Evidence*. Vol. 3, no. 1, pp. 5.

580 Hahn-Schilling, B. (1994) Struktur, sukzessionale Entwicklung und Bewirtschaftung selektiv
581 genutzter Moorwälder in Malaysia. Göttinger beiträge zur land- und forstwirtschaft in den
582 tropen und subtropen, Heft 94. Dissertation. Verlag Erich Goltze GmbH & Co. KG,
583 Göttingen.

584 Holden, J., Chapman, P., and Labadz, J. (2004) Artificial drainage of peatlands: hydrological
585 and hydrochemical process and wetland restoration. *Progress in Physical Geography*. Vol.
586 28, no. 1, pp. 95-123.

587 Huat, B., Kazemian, S., Prasad, A., and Barghchi, M. (2011) State of an art review of peat:
588 General perspective. *International Journal of the Physical Sciences*. Vol. 6, no. 8, pp. 1988-
589 1996.

590 Jauhiainen, J., Takahashi, H., Heikkinen, J., Martikainen, P., and Vasander, H. (2005) Carbon
591 fluxes from a tropical peat swamp forest floor. *Global Change Biology*. Vol. 11, no. 10, pp.
592 1788-1797.

593 Jauhiainen, J., Limin, S., Silvennoinen, H., and Vasander, H. (2008) Carbon dioxide and
594 methane fluxes in drained tropical peat before and after hydrological restoration. *Ecology*.
595 Vol. 89, no. 12, pp. 3503-3514.

596 Keddy, P., Fraser, L., Solomeshch, A., Junk, W., Campbell, D., Arroyo, M., and Alho, C.
597 (2009) Wet and wonderful: the world's largest wetlands are conservation priorities.
598 *BioScience*. Vol. 59, no. 1, pp. 39-51.

599

600 Koh, L.P., Miettinen, J., Liew, S.C., Ghazoul, J. (2011) Remotely sensed evidence of tropical
601 peatland conversion to oil palm. *Proceedings of the National Academy of Sciences of the*
602 *United States of America*, 108(12), pp.5127–32. Available at:

603 [http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3064377&tool=pmcentrez&rende](http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3064377&tool=pmcentrez&rendertype=abstract)
 604 [rtype=abstract](http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3064377&tool=pmcentrez&rendertype=abstract) [Accessed April 6, 2016].

605 Kuhry, P., and Vitt, D. (1996) Fossil carbon/nitrogen ratios as a measure of peat
 606 decomposition. *Ecology*. Vol. 77, no. 1, pp. 271-275.

607 Kumari, K. 1996. An application of the incremental cost framework to biodiversity
 608 conservation: a wetland case study in Malaysia. Centre for Social and Economic Research on
 609 the Global Environmental, 96-15.

610 Page, S., Siegert, F., Rieley, J., Böhm, H., Jaya, A., Limin, S. (2002) The amount of carbon
 611 released from peat and forest fires in Indonesia in 1997. *Nature*. Vol. 420, no. 6911, pp. 61–
 612 65.

613 Page, S., Wüst, R., Weiss, D., Rieley, J., Shotyk, W., and Limin, S. (2004) A record of Late
 614 Pleistocene and Holocene Carbon accumulation and climate change from an equatorial peat
 615 bog (Kalimantan, Indonesia): Implications for past, present and future carbon dynamics.
 616 *Journal of Quaternary Science*. Vol. 19, no. 7, pp. 625–636.

617 Page, S., Rieley, J., and Wüst, R. (2006) Lowland tropical peatlands of Southeast Asia. In:
 618 Martini, P., Martinez-Cortizas, A., and Chesworth, W. (editors), *Peatlands: basin evolution*
 619 *and depository of records on global environmental and climatic changes*. Amsterdam
 620 (Developments in Earth Surface Processes Series): Elsevier. pp. 145–72.

621 Posa, M., Wijedasa, L.S. and Corlett, R.T., 2011. Biodiversity and Conservation of Tropical
 622 Peat Swamp Forests. *BioScience*, 61(49), pp.49–57.

623 Price, J., and Schlotzhauer, S. (1999) Importance of shrinkage and compression in
 624 determining water storage changes in peat: the case of a mined peatland. *Hydrological*
 625 *Processes*. Vol. 13, no. 16, pp. 2591-2601.

626 Quinton, W., Gray, D., and Marsh, P. (2000) Subsurface drainage from hummock-covered
 627 hillslopes in the Arctic tundra. *Journal of Hydrology*. Vol. 237, no. 1, pp. 113-125.

628 Rieley, J. and Page, S. (2008) *Master Plan for the Rehabilitation and Revitalisation of the*
 629 *Ex-Mega Rice Project Area in Central Kalimantan* [online]. CARBOPEAT Technical
 630 Review No. 1. The Science of Tropical Peatlands and the Central Kalimantan Peatland
 631 Development Area. Euroconsult Mott MacDonald/Defltares/Delft Hydraulics. Available at:
 632 <http://www.geog.le.ac.uk/carbopeat/media/pdf/pub_technical_review%201-science.pdf>
 633 [Accessed 30 April 2015].

634 Rowell, D. (1994) The arrangement of particles and pores: soil structure. In: Rowell, D.
 635 (editor), *Soil Science: Methods and Applications*. Essex, England, Longman Scientific and
 636 Technical, pp. 61.

637 Sim, L., and Balamurugam, G. (1990) Hydrological functions. In: Prentice, C. (editor),
 638 *Environmental action plan for the North Selangor peat swamp forest*. AWB Publication,
 639 Asian Wetland Bureau/WWF—Malaysia.

640 Stanek, W., and Silc, T. (1977) Comparisons of four methods for determination of degree of
 641 peat humification (decomposition) with emphasis on the von Post method. *Canadian Journal*
 642 *of Soil Science*. Vol. 57, no. 2, pp. 109-117.

643 Tipping, E., Smith, E., Lawlor, A., Hughes, S., and Stevens, P. (2003) Predicting the release
 644 of metals from ombrotrophic peat due to drought-induced acidification. *Environmental*
 645 *Pollution*. Vol. 123, no. 2, pp. 239-253.

646 Vane, C. (2003a) Monitoring decay of black gum wood (*Nyssa sylvatica*) during growth of
 647 the shiitake mushroom (*Lentinula edodes*) using diffuse reflectance infrared
 648 spectroscopy. *Applied spectroscopy*. Vol. 57, no. 5, pp. 514-517.

649 Vane, C. (2003b). The molecular composition of lignin in spruce decayed by white-rot fungi
 650 (*Phanerochaete chrysosporium* and *Trametes versicolor*) using Pyrolysis–GC–MS and
 651 Thermochemolysis with Tetramethylammonium Hydroxide. *International Biodeterioration*
 652 *and Biodegradation*. Vol. 51, no 1, pp. 67-75.

653 Vane, C., Martin, S., Snape, C., Abbott, G.D. (2001) Degradation of lignin in wheat straw
 654 during growth of the Oyster mushroom (*Pleurotus ostreatus*) using off-line
 655 thermochemolysis with tetramethylammonium hydroxide and solid state ^{13}C NMR. *Journal*
 656 *of Agriculture and Food Chemistry*. Vol. 49, pp. 2709-2716.

657 Vane, C.H., Kim, A.W., Moss-Hayes V, Snape C.E, Castro-Diaz, M., Khan, N.S., Engelhart
 658 S.E. and Horton, B.P. 2013. Mangrove tissue decay by arboreal termites (*Nasutitermes*
 659 *acajutlae*) and their role in the mangrove C cycle (Puerto Rico): Chemical characterisation
 660 and organic matter provenance using bulk $\delta^{13}\text{C}$, C/N, alkaline CuO oxidation-GC/MS and
 661 solid-state ^{13}C NMR. *Geochemistry, Geophysics, Geosystems* Vol. 14, no 8, pp. 3176-3191.

662 Verry, E., Boelter, D., Päivänen, J., Nichols, D., Malterer, T., and Gafni, A. (2011) Physical
 663 Properties of Organic Soils. In: Kolka, R., Sebestyen, S., Verry, E., and Brooks, K. (editors),
 664 *Peatland Biogeochemistry and Watershed Hydrology at the Marcell Experimental Forest*.
 665 United States of America, CRC Press: Taylor and Francis Group, pp. 136 -137.

666 von Post, L. (1922) Sveriges Geologiska Undersöknings torvinventering och några av dess
 667 hittills vunna resultat. Svenska Mosskulturföreningens, Tidskrift. Vol. 1, pp. 1-27.

668 Wetlands International (2014) *Tropical Peat Swamp Forests* [online]. Wetlands International,
 669 Netherlands. Available at:
 670 <[http://www.wetlands.org/Whatarewetlands/Peatlands/Tropicalpeatswampforests/tabid/2739/](http://www.wetlands.org/Whatarewetlands/Peatlands/Tropicalpeatswampforests/tabid/2739/Default.aspx)
 671 [Default.aspx](http://www.wetlands.org/Whatarewetlands/Peatlands/Tropicalpeatswampforests/tabid/2739/Default.aspx)> [Accessed 02 November 2014].

672 Wösten, J., Ismail, A., and Van Wijk, A. (1997) Peat subsidence and its practical
673 implications: a case study in Malaysia. *Geoderma*. Vol. 78, no. 1-2, pp. 25-36.

674 Wösten, J., Clymans, E., Page, S., Rieley, J., and Limin, S. (2008) Peat–water
675 interrelationships in a tropical peatland ecosystem in Southeast Asia. *Catena*. Vol. 73, no. 2,
676 pp. 212-224.

677 Wüst, R., Bustin, R., and Lavkulich, L. (2003) New classification systems for tropical
678 organic-rich deposits based on studies of the Tasek Bera Basin, Malaysia. *Catena*. Vol. 53,
679 no. 2, pp.133-163.

680 Yonebayashi, K., Pechayapisit, J., Vijarnsorn, P., Zahari, A., and Kyuma, K. (1994)
681 Chemical alterations of tropical peat soils determined by Waksman's proximate analysis and
682 properties of humic acids. *Soil Science and Plant Nutrition*. Vol. 40, no. 3, pp. 435-444.

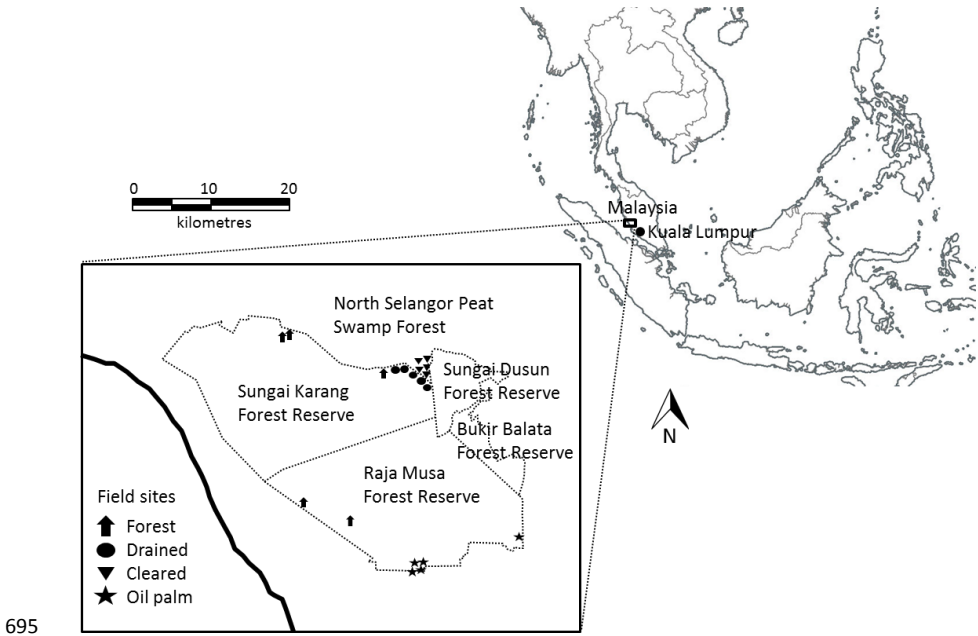
683 Yule, C., and Gomez, L. (2009) Leaf litter decomposition in a tropical peat swamp forest in
684 Peninsular Malaysia. *Wetlands Ecology and Management*. Vol. 17, no. 3, pp. 231-241.

685 Yusop, Z. (2002) Hydrological attributes of a disturbed peat swamp forest. In: Parish, F.,
686 Padmanabhan, E., Lee, C., and Thang, H. (editors), *Prevention and control of fire in*
687 *peatlands*. Proceedings of workshop on prevention and control of fire in peatlands, 19–21
688 March 2002, Kuala Lumpur. Global Environment Centre and Forestry Department Peninsular
689 Malaysia. Cetaktama, Kuala Lumpur, pp. 51–56.

690 Zhang, R. (1997) Determination of soil sorptivity and hydraulic conductivity from the disk
691 infiltrometer. *Soil Science Society of America Journal*. Vol. 61, no. 4, pp. 1024-1030.

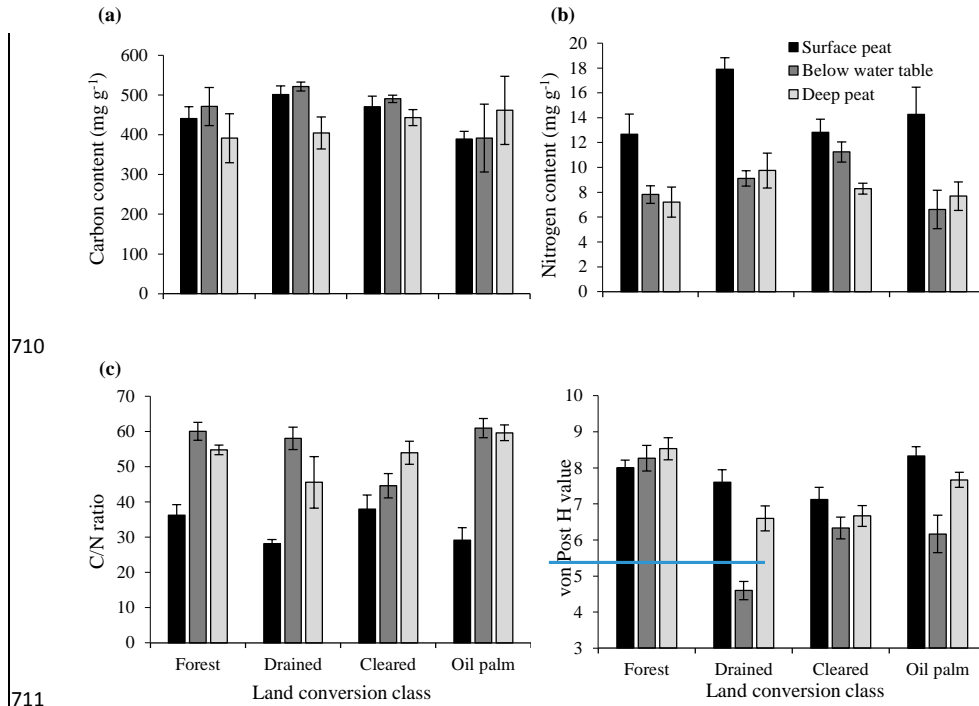
692

693 **Figures**
694



695
696 **Figure 1:** Location of North Selangor Peat Swamp Forest and field plots.

708
709



711

712 **Figure 2:** The difference in (a) carbon content; (b) nitrogen content; and (c) C/N ratio between secondary peat,
713 and (d) degree of decomposition indicated by the H value among secondary peat swamp forests, drained peat
714 swamp forests, cleared peat swamp forests, and mature oil palm plantations at three different depths within the
715 peat profiles: surface peat (black bar); below the water table (dark grey bar); and deep peat (light grey bar).
716 Average values for land conversion classes and standard error bars are shown.

717 (a) Land conversion class: $F_{(3,44)}=1.97$, $P=0.133$; Depth: $F_{(2,44)}=2.26$, $P=0.116$; Interaction: $F_{(6,44)}=0.84$, $P=0.544$
718 (b) Land conversion class: $F_{(3,44)}=3.25$, $P=0.031$; Depth: $F_{(2,44)}=28.21$, $P<0.001$; Interaction: $F_{(6,44)}=1.61$,
719 $P=0.166$
720 (c) Land conversion class: $F_{(3,44)}=1.80$, $P=0.16$; Depth: $F_{(2,44)}=47.17$, $P<0.001$; Interaction: $F_{(6,44)}=3.25$, $P=0.01$

721

722 (d) Land conversion class: $F_{(3,269)}=56.77, P<0.001$; Depths: $F_{(2,269)}=92.87, P<0.001$; Interaction: $F_{(6,269)}=12.08,$
723 $P<0.001$

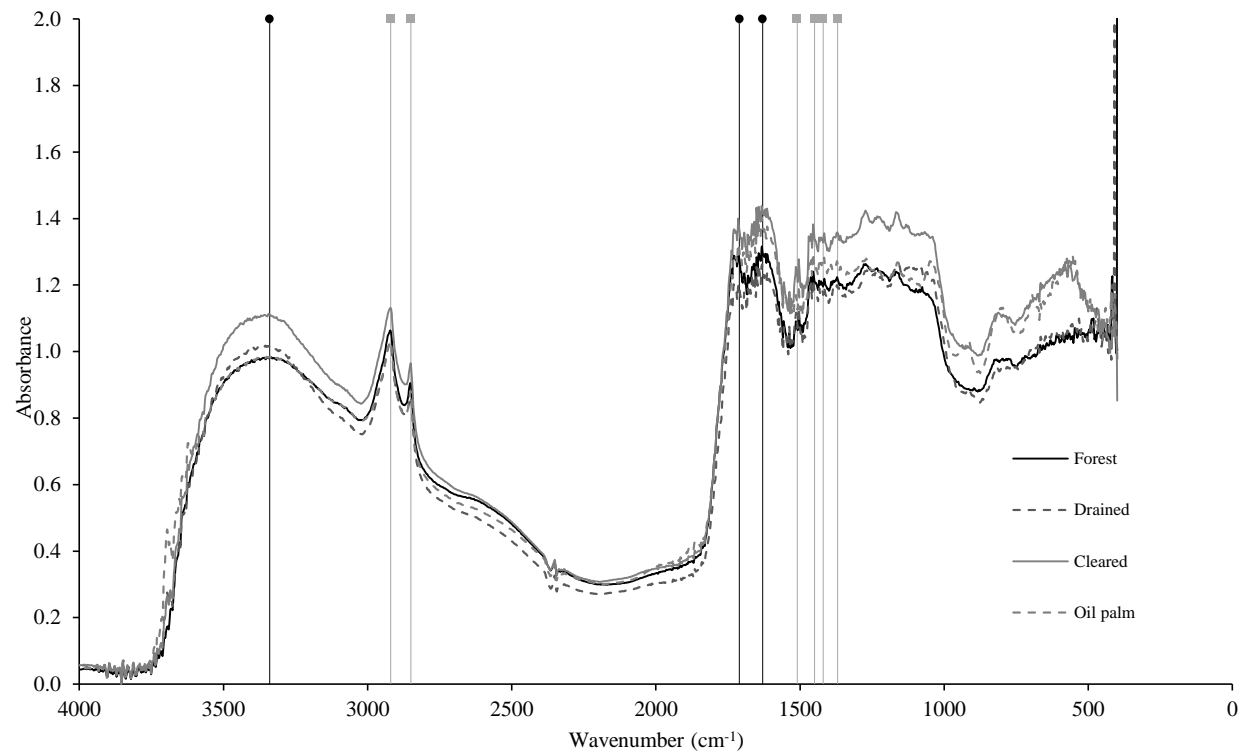


Figure3: DRIFT spectra of the average surface peat samples from 0-10 cm for: secondary peat swamp forests (black line), drained peat swamp forests (black dashed line), cleared peat swamp forests (grey line), and mature oil palm plantations (grey dashed line). Vertical black lines indicate the peaks at wavenumbers 3340, 1710, and 1630 cm^{-1} of which significantly different ratios were found between land conversion classes, and vertical grey lines indicate the peaks at wavenumbers 2920, 2850, 1510, 1450, 1420, and 1370 cm^{-1} common to tropical peats.

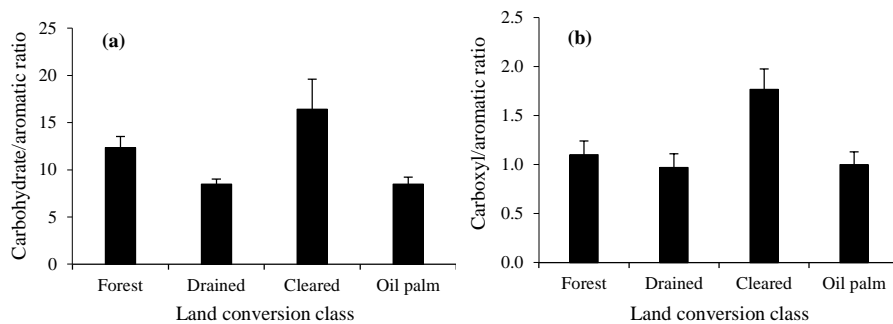


Figure 4: The difference in (a) ~~3340/1630-ratio or~~ carbohydrate/aromatic ratio [i.e. 3340/1630 ratio or](#); and (b) ~~1710/1630 or~~ carboxyl/aromatic [ratio i.e. 1710/1630-ratio](#) ~~between-among~~ secondary peat swamp forests, drained peat swamp forests, cleared peat swamp forests, and mature oil palm plantations in surface peat. Average values for land conversion classes and standard error bars are shown: (a) $F_{(3,16)}=5.64$, $P=0.008$; (b) $F_{(3,16)}=5.62$, $P=0.008$.

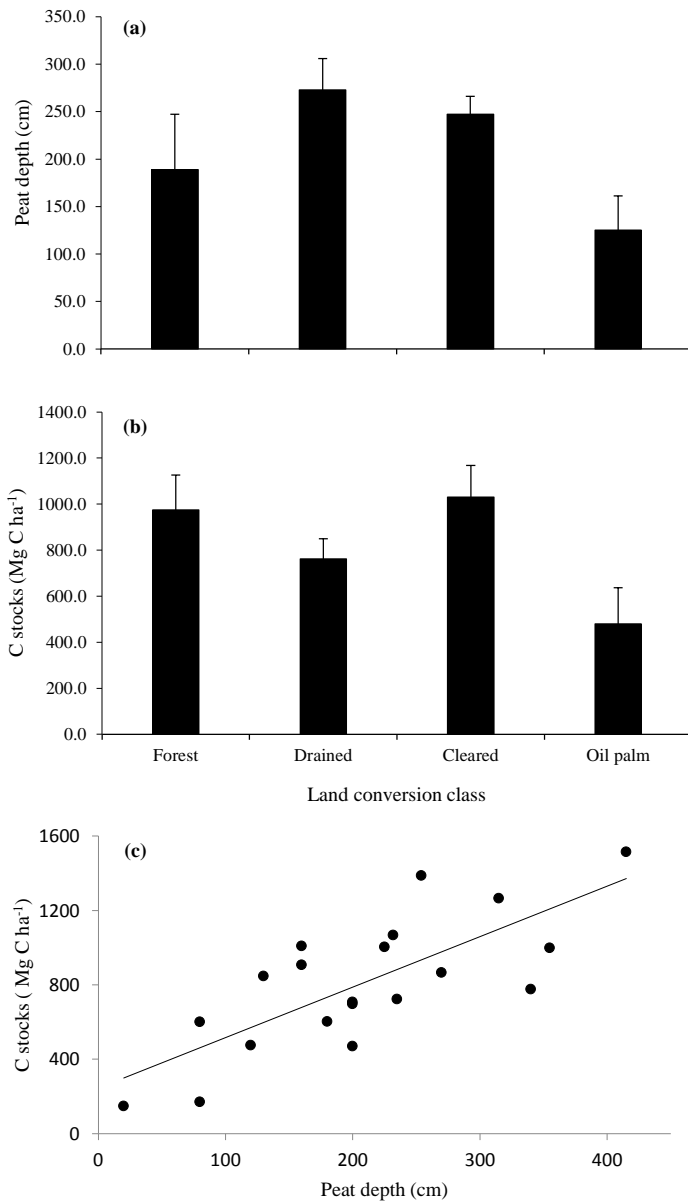


Figure 5: (a) Peat depth; and (b) C stocks at the different land conversion classes. Average values for land conversion classes and standard error bars are shown. Significant differences among land conversion classes: (a) $F_{(3,19)}=2.81$, $P=0.07$; (b) $F_{(3,19)}=4.11$, $P=0.02$. (c) Relationship between peat depth and C stocks; $F_{(1,19)}=24.05$, $P<0.001$, $R^2=0.55$.

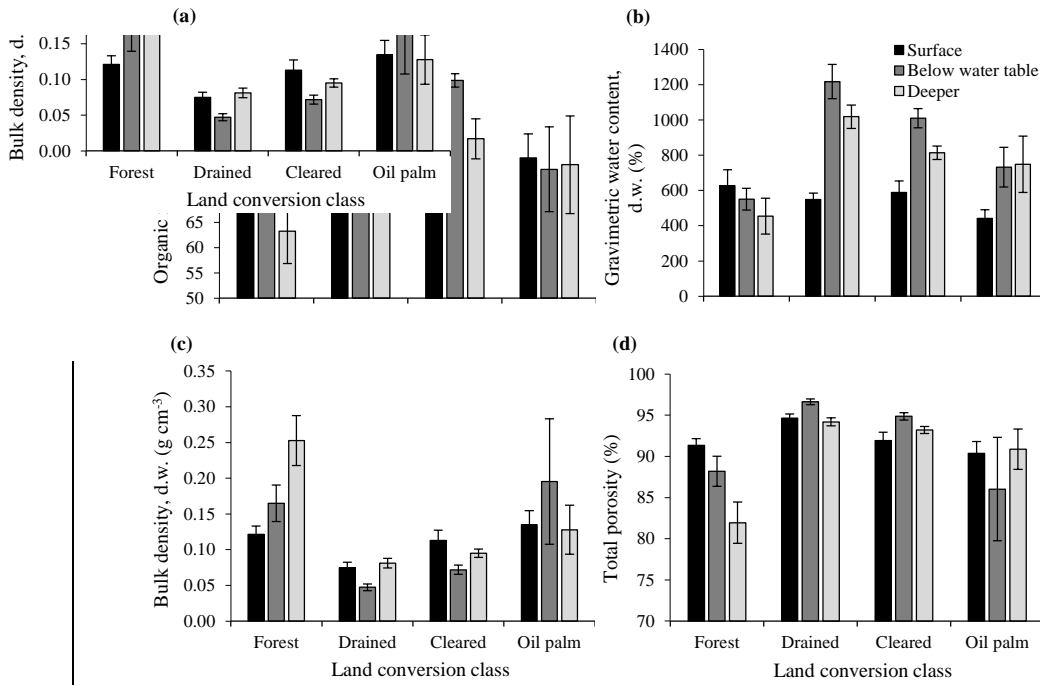


Figure 6: The difference in (a) organic matter content; (b) gravimetric water content (dry weight basis); (c) total porosity; and (d) bulk density (dry weight basis) between secondary peat swamp forests, drained peat swamp forests, cleared peat swamp forests, and mature oil palm plantations at three different depths within the peat profiles: surface peat (black bar); below the water table (dark grey bar); and deep peat (light grey bar). Average values for land conversion classes and standard error bars are shown.

(a) Land conversion class: $F_{(3,156)}=5.44$, $P=0.001$; Depth: $F_{(2,156)}=9.19$, $P<0.001$; Interaction: $F_{(6,156)}=2.66$, $P=0.017$

(b) Land conversion class: $F_{(3,156)}=17.93$, $P<0.001$; Depth: $F_{(2,156)}=17.31$, $P<0.001$; Interaction: $F_{(6,156)}=5.31$, $P<0.001$

(c) Land conversion class: $F_{(3,156)}=21.47$, $P<0.001$; Depth: $F_{(2,156)}=5.47$, $P=0.005$; Interaction: $F_{(6,156)}=2.22$, $P=0.044$

(d)

(e)(d) Land conversion class: $F_{(3,156)}=19.43$, $P<0.001$; Depth: $F_{(2,156)}=4.33$, $P=0.015$; Interaction: $F_{(6,156)}=2.21$, $P=0.044$

(d)(a) Land conversion class: $F_{(3,156)}=21.47$, $P<0.001$; Depth: $F_{(2,156)}=5.47$, $P=0.005$; Interaction: $F_{(6,156)}=2.22$, $P=0.044$

